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Higher minimum dissolved oxygen concentrations increase penaeid shrimp yields in earthen ponds

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Abstract

Nine 0.11-ha earthen ponds were stocked on 15 May 1997 with *Litopenaeus vannamei* and *L. stylirostris* postlarvae in similar proportions at a total density of 33 animals/m^2. Ponds were equipped with automated temperature and dissolved oxygen (DO) concentration data acquisition devices that sampled ponds every 30 min. Aspirator-pump aerators (0.75 kW) were automatically activated when DO fell to 65% (4.6 mg/l at 29°C and 15 ppt salinity), 40% (2.8 mg/l at 29°C and 15 ppt), or 15% (1.1 mg/l at 29°C and 15 ppt) of saturation. Mean shrimp yield, survival of both species, and profitability increased linearly as minimum DO concentration increased from 15% to 65% of saturation ($P < 0.05$). Higher yields were positively correlated with higher survivals. Final mean shrimp weights were not significantly affected by minimum DO concentrations ($P > 0.05$).

Keywords: Dissolved oxygen; Shrimp; Aeration

1. Introduction

As the shrimp aquaculture industry strives to minimize its environmental impact, water exchange rates will be reduced and the need for aeration will increase. As aeration usage increases, knowledge of optimal levels of aeration becomes more important.

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Biochemical oxygen demand (BOD) of intensive shrimp ponds usually exceeds autochthonous oxygen production. Daily water exchange of 15–70% of pond volume traditionally has been used to reduce BOD loading to help maintain appropriate DO concentrations (Hopkins et al., 1993). In the USA, the regulation of pond discharge as a source of nutrient enrichment in receiving waters has resulted in efforts to minimize water exchange (Hopkins et al., 1993; Wang, 1990). In the absence of water exchange, aeration is essential to satisfy pond BOD.

Aeration has been used to improve water quality and increase yields in aquaculture ponds. Yields in catfish ponds stocked at $1/m^2$ increased from 3657 to 4813 kg/ha by applying aeration at 6.25 kW/ha, for 6 h nightly (Lai-fa and Boyd, 1988). Shrimp production increased from 2061 to 2852 kg/ha in Hawaii through the use of paddle-wheel aeration applied at 3.7 kW/ha, 24 h/day (Wyban et al., 1989).

Continuous aeration has been reported in intensively managed shrimp ponds (Wyban et al., 1989; Hopkins et al., 1992, 1993). However, the operation of aerators during daylight hours when photosynthetic activity is high may result in the deoxygenation of supersaturated pond water. Considerable economic benefit may be obtained by restricting aeration to periods of need, particularly in regions where the cost of electricity is differentially high during the day.

Ponds stocked with shrimp at $25–40/m^2$ typically are aerated at rates of 3.7–14.9 kW/ha. Actual consumption of electricity is 1.26 times shaft power (Ahmad and Boyd, 1988), so hourly electricity consumption would vary from 4.7 to 18.8 kW. At US$0.08/kW h, hourly electricity costs could range from US$0.38 to US$1.50. For a culture period of 120 days, electricity consumption could cost from US$1083 to US$4331/ha if applied for 24 h/day. This cost would be reduced to US$541–2166 if aerators were operated only 12 h/night. A concern shared by most producers is to know when aerators should be activated to maximize profits. DO concentrations near saturation may result in maximum production, but the energy costs to maintain saturated conditions may exceed the value of higher production. Automated data acquisition devices are available to monitor DO concentrations and other water quality parameters (Ebeling and Losordo, 1989; Green and Teichert-Coddington, 1991). Hoagland et al. (2000) demonstrated that electricity consumption could be reduced in shrimp ponds by using these automated systems to activate aerators when DO concentration reached a set threshold concentration.

The objectives of this study were to determine the effects of maintaining different minimum concentrations of DO on gross yield, survival and growth of *Litopenaeus vannamei* and *L. stylirostris*.

2. Materials and methods

This study was conducted at the Claude Peteet Mariculture Center in Gulf Shores, AL. Nine 0.11-ha rectangular ponds lined with high-density, black polyethylene plastic were used in this study. Pond bottoms contained 30 cm of native soil. Water levels were adjusted so that pond depths averaged 1 m, and pond volumes averaged 888 m^3.

Pond preparation included drying and the application of agricultural lime at 455 kg/ha. A herbicide (Rodeo™) was applied at the recommended rate to dry pond bottoms 1 month prior to stocking to eliminate emergent vegetation. After filling, the ponds were fertilized with 9.1 kg of menhaden meal and 2 l of 38-8-0 liquid fertilizer 3 days before shrimp were stocked. A 1:16 mixture of motor oil and diesel fuel was applied evenly over the water surface in all ponds 24 h before stocking to eliminate/reduce populations of air-breathing insects.

Three treatments were assigned randomly to the nine ponds so that each treatment had three replicates. Treatments consisted of the activation of aerators at (1) 65% of saturation (4.6 mg/l), (2) 40% of saturation (2.8 mg/l), or (3) 15% of saturation (1.1 mg/l). The dissolved oxygen concentrations at saturation were calculated for 29°C and 15 ppt salinity. The ponds were equipped with automated temperature and dissolved oxygen (DO) concentration data acquisition devices (AutoHand™) that consisted of one self-cleaning and calibrating sensing unit in the middle of each pond that was wired to a control panel at the pond side. Temperature and DO determinations were made every 30 min at approximately 50-cm depth. Aspirator-pump aerators (0.75 kW) were installed in all the ponds and were activated automatically when the DO declined to the prescribed treatment saturation level. A watt-hour meter monitored energy consumption of aerators in each pond.

Nearly equal number of SPF *L. vannamei* and *L. stylirostris*, purchased from Makuu Aquafarms, HI, was stocked in each pond, providing a total density of 33 postlarval shrimp/m^2. Beginning 5 days after stocking, 10 kg/ha of feed (Burris Mill & Feed, Franklinton, LA) containing 35% crude protein was applied until the shrimp were large enough to be sampled with a seine (day 28). A sample of 50 shrimp, with roughly equal number of both species, was taken weekly from each pond thereafter to monitor growth and to adjust the feeding rates. The initial daily feeding rate of 5% of body weight decreased to a final rate of 3% as shrimp increased in weight. An assumed survival rate of 75% was used for feed calculations. Equal quantities of feed were applied to all ponds in the same treatment. The maximum feeding rate did not surpass 91 kg/ha/day. Water was exchanged weekly at 20% of pond volume in all ponds during the last month of the study to help maintain the minimum DO for each treatment.

Weekly water samples were obtained from each pond between 0630 and 0800 h with a 100-cm column sampler (Boyd and Tucker, 1992). Subsamples were collected from three locations in the deep section of each pond and combined for water analysis in the laboratory.

The pH of water samples was determined immediately after collection. Early morning (0600 h) and late afternoon (1700 h) pH values were determined during the last 6 weeks of the study. Total ammonia, nitrite and chlorophyll *a* were determined according to Strickland and Parsons (1972). Total suspended solids, total volatile suspended solids, and total fixed solids (ash) were determined according to Standard Methods (APHA et al., 1989), except that filters were washed with distilled water to remove salts following filtration.

Ponds were stocked on 15 May 1997 and harvested on 15 October 1997. Shrimp were sampled on a weekly basis during the culture period. Harvested shrimp were weighed to determine gross yield. The mean individual shrimp weight of each species in

Table 1
Mean production (s.e.) of marine shrimp stocked in ponds aerated to maintain minimum dissolved oxygen concentrations above 15%, 40%, or 65% of saturation

Treatment	Total yield (kg/ha)	Overall survival (%)	*L. vannamei*		*L. stylirostris*		FCR	Electricity (kW h/ha)	Net income[a] (US$/ha)	Yield/energy use (kg/ha/kW h)
			Survival (%)	Mean weight (g)	Survival (%)	Mean weight (g)				
15% Saturation	2976 (10.2)	42 (2.0)	57 (2.7)	22 (0.9)	24 (1.0)	17 (0.9)	2.64 (0.06)	3527 (51.1)	20,147 (606)	0.87 (0.122)
40% Saturation	3631 (44.7)	55 (4.4)	73 (3.7)	21 (1.2)	32 (5.2)	17 (0.3)	2.21 (0.22)	5093 (63.6)	24,545 (2760)	0.73 (0.103)
65% Saturation	3975 (24.2)	61 (1.9)	71 (4.4)	21 (0.6)	47 (1.8)	17 (0.7)	1.96 (0.11)	9014 (59.2)	26,696 (1498)	0.44 (0.034)
Orthogonal linear contrast	s	hs	s	ns	hs	ns	s	hs	s	s

Equal proportions of *L. vannamei* and *L. stylirostris* were stocked into ponds to give a total stocking rate of 33 PLs/m^2.
s = significant ($P < 0.05$); hs = highly significant ($P < 0.01$); ns = not significant ($P > 0.05$).
[a]Net income = total income − cost of feed and electricity.

each pond was determined by weighing to the nearest 0.1 g at least 100 individuals that had been collected at random from harvest containers. One-way ANOVA and orthogonal linear contrasts (SuperANOVA, Abacus Concepts, Berkeley, CA, USA) were used to evaluate if there were significant responses ($P < 0.05$) to an increase in the minimal concentration of dissolved oxygen. Survival data of harvested shrimp were arcsine

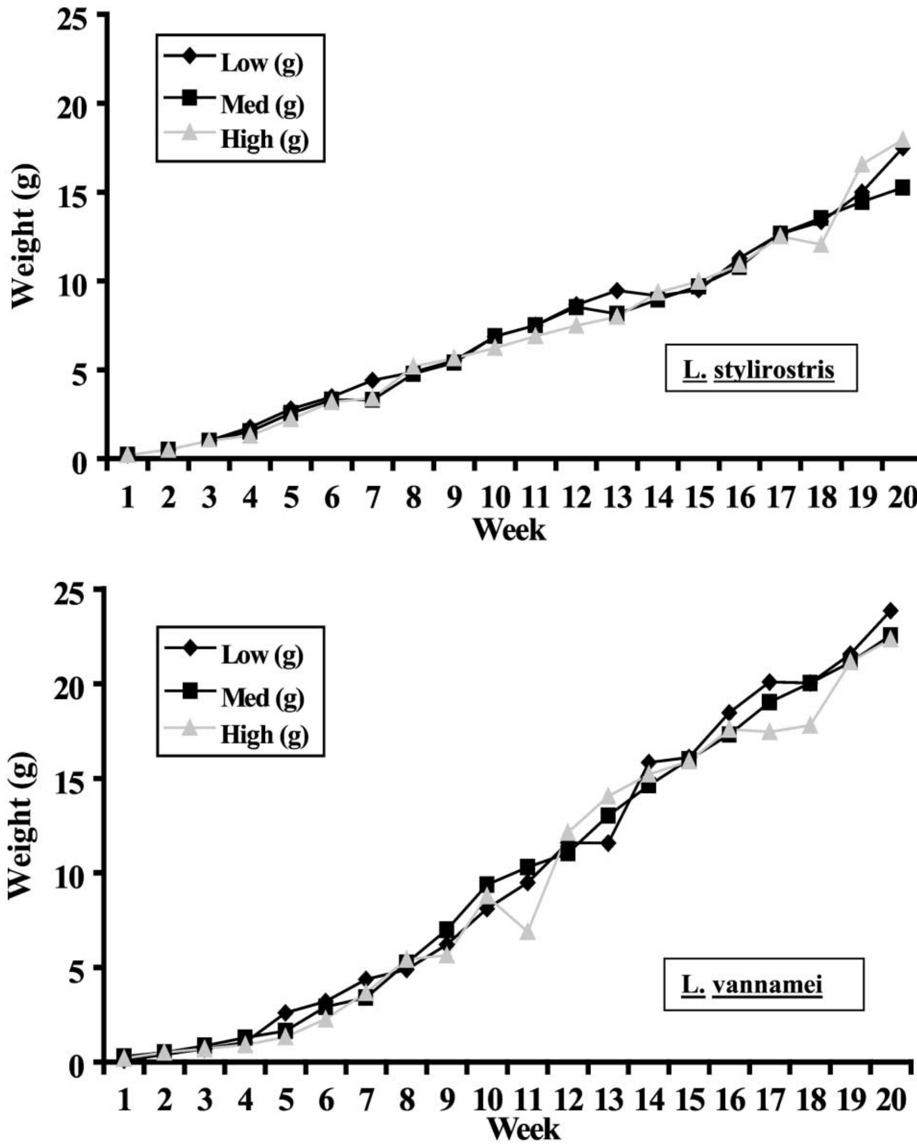

Fig. 1. Mean growth rates of *L. stylirostris* and *L. vannamei* in ponds aerated to maintain minimum dissolved oxygen concentrations above 15% (Low), 40% (Med.), or 65% (High) of saturation.

transformed and pH data were transformed to the H^+ ion concentration prior to statistical analyses.

3. Results

Mean shrimp yield (2976–3975 kg/ha) increased linearly as minimum DO concentration increased from 15% to 65% of saturation ($P < 0.05$) (Table 1). Mean shrimp growth over time for either species was similar among the three treatments (Fig. 1). The average weekly weight gain during the final 16 weeks of culture was 1.27 g for *L. vannamei* and 0.97 g for *L. stylirostris*. The final mean weight of *L. vannamei* (21 g) was significantly greater than the mean weight of *L. stylirostris* (17 g) ($P < 0.01$). Mean final individual shrimp weights within species were not affected by treatment ($P > 0.05$) (Table 1). The survival of both shrimp species decreased with decreasing minimum DO. *L. stylirostris* appeared to be more sensitive to low DO than did *L. vannamei*, because *L. stylirostris* survival was significantly lower ($P < 0.01$). Mean *L. stylirostris* survival

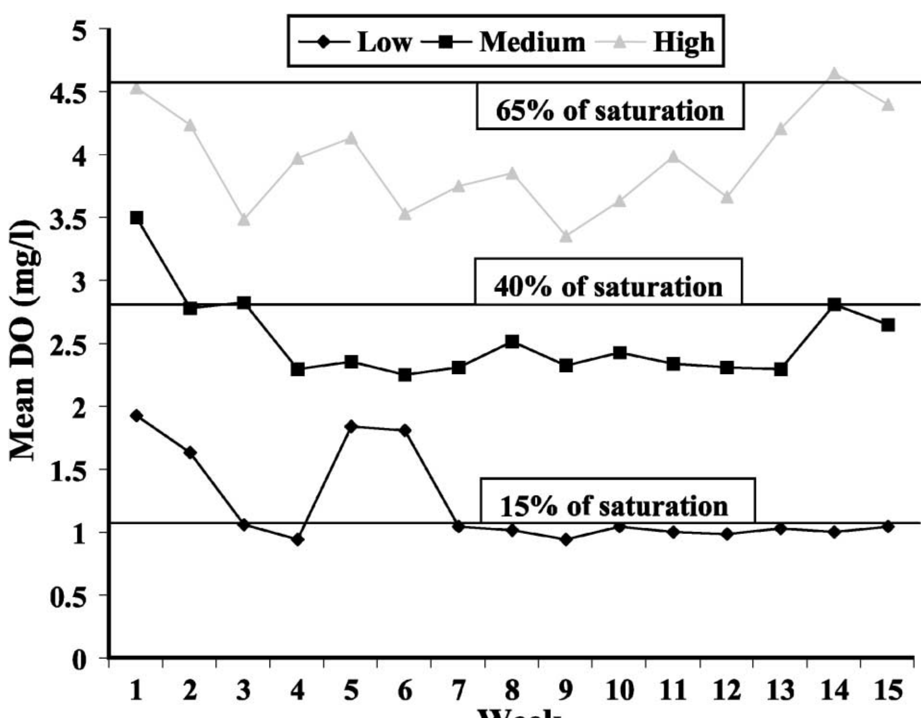

Fig. 2. Weekly mean minimum dissolved oxygen concentration for earthen ponds in which aerators were automatically activated at 15% (Low), 40% (Med.), or 65% (High) of saturation. If the DO did not fall below the minimum treatment value, then the lowest DO for that period was used.

for all treatments was 34%, ranging from 23% to 50%. In comparison, *L. vannamei* mean survival was 67%, ranging from 53% to 80%. High treatment yields were directly correlated with high treatment survival. Mean feed conversion ratios (FCR) increased from 1.96 to 2.64 with decreasing minimum DO. Feeding rate calculations assumed a 75% survival. Because survival of shrimp in low DO ponds was less than 75%, these ponds were overfed causing a higher FCR.

Maintenance of a higher DO concentration increased electricity consumption ($P < 0.05$) (Table 1). Shrimp yield per unit of electricity consumption decreased as greater energy was required to maintain higher DO concentrations ($P < 0.05$) (Table 1). However, income from higher shrimp yields more than compensated for increased energy costs. Net income increased as the minimal DO was increased from 15% to 65% of saturation ($P < 0.05$) (Table 1).

Aerators were activated at selected threshold concentrations, but the aeration power was not always adequate to maintain the DO at specified concentrations. The lowest treatment threshold concentration (15% saturation) was easiest to maintain, and the highest threshold (65%) was the most difficult (Fig. 2). As expected, aerators were required to operate more hours to maintain the higher threshold concentrations (Fig. 3, Table 1).

Chlorophyll *a*, nitrite, and total ammonia were not significantly affected by aeration treatments (Table 2). Observed mean values of morning pH, and concentrations of total suspended solids, total volatile solids and ash increased with increasing aeration, but not significantly ($P > 0.05$). As expected, mean early morning DO concentration for the culture period significantly increased with increasing aeration. Mean salinity and temperature of ponds for the production season were 8.3 ppt and 29.8°C, respectively.

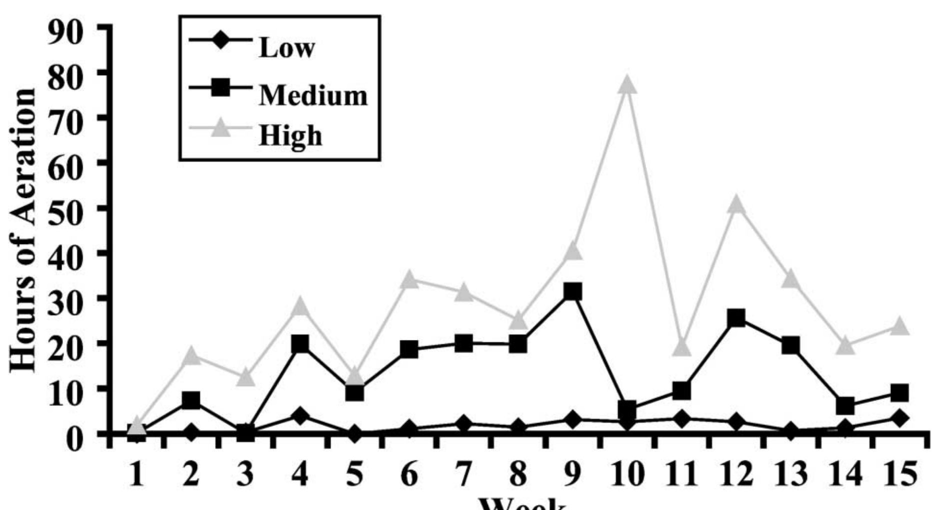

Fig. 3. Mean weekly number of hours that aerators operated when automatically activated at 15% (Low), 40% (Med.), or 65% (High) of saturation.

Table 2
Mean (s.e.) pond water quality variables in shrimp ponds stocked at 33 PL/m^2 and aerated to maintain minimum dissolved oxygen concentrations above 15%, 40%, or 65% of saturation

Treatment	Chlorophyll *a* (μg/l)	Total ammonia (mg/l)	Nitrite (mg/l)	Total solids (mg/l)	Volatile solids (mg/l)	Ash (mg/l)	Morning DO (mg/l)	Morning pH	Afternoon pH
15% Saturation	139 (26.7)	0.33 (0.076)	0.03 (0.010)	66 (7.1)	45 (2.1)	21 (5.4)	2.3 (0.37)	7.8 (8.27)	8.6 (8.81)
40% Saturation	122 (4.8)	0.52 (0.060)	0.03 (0.010)	70 (3.5)	46 (1.5)	24 (2.0)	2.96 (0.07)	8.0 (9.36)	8.1 (8.31)
65% Saturation	126 (21.6)	0.34 (0.070)	0.04 (0.020)	75 (17.2)	48 (8.2)	27 (9.6)	3.9 (0.08)	8.2 (9.21)	8.4 (9.46)
Orthogonal linear contrast	ns	ns	ns	ns	ns	ns	hs	ns	ns

s = significant ($P < 0.05$); hs = highly significant ($P < 0.01$); ns = not significant ($P > 0.05$).

4. Discussion

Shrimp yield was lowest at the lowest threshold DO concentration for activating aerators, because survival was lowest at this concentration. Individual growth of shrimp did not vary because of different minimal DO concentrations. Other researchers have reported combinations of decreased survival, decreased individual growth, and decreased feed consumption for other species cultured in low DO situations. Channel catfish (*Ictalurus punctatus*) produced in tanks with DO concentrations maintained at 36% of saturation had severely reduced feed consumption and efficiency compared with fish produced at 100% or 60% of DO saturation (Andrews et al., 1973). Production of white catfish (*I. catus*) in earthen ponds increased linearly with increasing levels of diffused air aeration (Loyacano, 1974). Greater harvest yields were attributed to an increase in both catfish survival and mean individual growth. Poorer feed conversion and less feed consumption were reported in channel catfish ponds with low DO (Lai-fa and Boyd, 1988; Boyd, 1990). Thromford and Boyd (1991) reported higher catfish survival and yields in ponds where aeration was used nightly when compared with ponds where only emergency aeration was used. Teichert-Coddington and Green (1993) observed less feed consumption and slower individual growth when tilapia were exposed to daily low DO less than 30% of saturation.

Data on the response of shrimp to low DO concentrations are less available. Mean shrimp yield was significantly greater in shrimp ponds aerated with 3.1 kW/ha diffused air for 12–24 h/day (1687–1813 kg/ha) when compared with non-aerated ponds (1243 kg/ha) (Martinez-Cordova et al., 1998). Yields were lower in non-aerated ponds because survival was significantly lower, probably because early morning DO reached 0.6 mg/l in these ponds. Seidman and Lawrence (1985) tested *L. vannamei* in a recirculating tank system for 16 days with DO concentrations maintained at 1.17, 1.91, 3.10 or 4.01 mg/l. Mean shrimp weight for the lowest DO treatment was significantly less than in other treatments, but digestibility of feed and survival were similar for all treatments.

The tank study for shrimp (Seidman and Lawrence, 1985) was different from this pond study. The DO concentrations in tanks were maintained at a given level throughout the day, but the DO concentrations in ponds increased up to or above saturation most days because of photosynthesis. The daily high DO concentrations for ponds in which the minimum DO thresholds were maintained, probably resulted in temporarily acceptable conditions, under which shrimp could consume and digest food.

Shrimp yield increased as the threshold DO increased, but the yield per unit increase of aeration energy consumption declined with increasing aeration. This decline may be attributable to two factors. First, the oxygen transfer rate of aerators is dependent on the difference between the actual DO concentration and the DO concentration at saturation (Boyd, 1990). As the DO concentration approaches saturation, the rate of oxygen transfer declines logarithmically. Therefore, aerators must operate longer and consume more energy for each incremental increase in DO as the saturation concentration is approached. Second, the positive response that shrimp demonstrated to higher minimum DO apparently declined as DO approached saturation. Profitability was highest at the highest threshold DO, but the declining yield per unit increase of energy consumption indicated that the aerator operation costs may eventually exceed the revenue gained from increased aeration. A demonstration of this principle may be encountered in the study by Thromford and Boyd (1991) in which nightly aeration of catfish ponds was significantly more profitable than emergency aeration, but continual aeration was no more profitable than nightly aeration.

Aeration was found to increase suspended solids in catfish ponds in Alabama (Thromford and Boyd, 1991) and in tilapia ponds in Honduras (Teichert-Coddington and Green, 1993). Total suspended solids did not significantly increase with greater aeration in this study, probably because it was accomplished in brackish water ponds lined with polyethylene and refilled with sandy soil (7% clay). By comparison, the studies in Alabama and Honduras were undertaken in freshwater earthen ponds with soils containing 35% (Munsiri et al., 1996) to 50% clay (Green et al., 1990). Boyd (1990) indicated that most suspended fixed solids in ponds are clay particles maintained in suspension by slow settling velocities and the repelling effect of negatively charged surfaces. High concentrations of anions in saline water neutralize the negative charges on clay particles thereby promoting flocculation (Day et al., 1989).

Emergency aeration and water exchange traditionally are undertaken to mitigate low DO when concentrations decline to 2–3 mg/l. Results from this study suggest that remedial action should begin sooner. Highest yields and profits were obtained when aerators were activated at about 65% of saturation, or 4.6 mg/l at 29°C and 15 ppt. Although the aerators were activated at this point, the minimum DO concentration periodically declined to about 3.8 mg/l, or close to 50% of saturation. When aeration was initiated at 40% of saturation, DO frequently declined to about 35% of saturation, or 2.5 mg/l (Fig. 3). These results indicate that 7.5 kW/ha of aeration with an aspirator pump was insufficient to maintain DO exactly at the concentration desired for this experiment. On a practical basis, aerators should be activated early enough and aeration power should be great enough to ensure that DO concentration does not decline below 50% of saturation.

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